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ORIGINALS ORIGINALARBEITEN

Service life of timber components: prognosis based on 3 years high-frequency monitoring

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Abstract Within this study various timber components were monitored highly frequently in terms of wood moisture content and wood temperature over a period of 3 years. The data sets were applied to a logistic dose–response performance model which is based on dose functions considering wood moisture content and temperature as key factors for fungal decay. The response in terms of certain decay levels was used to characterize different limit states and thus the expected service life. Service lives were prognosticated for wooden fence posts, lattices, terrace decking, and façades with different orientations, heights above ground and roof overhangs. Significant differences were found between the various commodities and the three investigated wood species which were Norway spruce (*Picea abies* Karst.), Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco).

Gebrauchsdauer von Holzbauteilen: Vorhersagen auf Basis eines dreijährigen Monitorings

Zusammenfassung Im Rahmen dieser Studie wurden Holzbauteile hinsichtlich Holzfeuchte und Holztemperatur während drei Jahren überwacht. Ein logistisches Performance-Modell wurde auf die gewonnenen Datensätze angewendet und auf Basis von Dosis-Wirkungsfunktionen wurde die zu erwartende Gebrauchsdauer von Holzpfählen, Zaunlatten, Terrassendecks und Fassaden mit unterschiedlichen Ausrichtungen, Abständen zum Boden und Dachüberständen prognostiziert. Signifikante Unterschiede ergaben sich zwischen den unterschiedlichen Bauteilen und den drei untersuchten Holzarten Fichte (*Picea abies* Karst.), Kiefernsplint (*Pinus sylvestris* L.) und Douglasie (*Pseudotsuga menziesii* Franco).

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1 Introduction

The functional service life of timber structures is predominantly affected by the interdependency of wood resistance on the one hand and climatic loads on the other hand. Biological degradation in terms of fungal decay is the most common reason for structural failures. Therefore consolidated knowledge of the interrelationship between the intensity of fungal degradation over time and the numerous decay-influencing factors is needed to estimate the service life to be expected for wooden components in outdoor applications. In principal, there are three different sources providing information about decay processes. 1. Laboratory experiments, 2. field trials, and 3. surveys on structures in service (in-service performance). Laboratory tests allow setting up exactly defined conditions, e. g., in terms of moisture, temperature, and organisms involved. On the other hand it is difficult to mimic real life conditions in the laboratory, because many factors occurring in the field are not reproducible or are even unknown. Field tests are more time-consuming compared to laboratory tests, but closer to reality (Hedley 1993; Nilsson and Edlund 1995; Augusta 2007). While the test setup may be identical, the local climate conditions vary from one trial to the other in dependence of time and site. As a matter of course most realistic conditions appear on real buildings and building

components. Surveys on such structures in service are therefore a very important data source (Gobakken et al. 2008; Brischke and Rolf-Kiel 2010). However, in most cases they suffer from long exposure times until decay occurs or lacking information about their history (initial protection measures, environmental conditions during exposure, and maintenance intervals).

The establishment of dose–response functions as described for instance by Brischke and Rapp (2010) and Isaksson et al. (2012) allows overcoming the drawback of long exposure times needed for field trials. Once the interrelationship between the most important decay influencing factors wood moisture content and wood temperature (dose) and fungal decay (response) is determined in long-term field experiments (dose–response functions), the impact of further decay factors may be quantified in terms of dose-time functions. To determine dose-time functions high-frequent medium-term recordings ($\sim$3 years) of moisture content and temperature will be sufficient, because it is no longer necessary to await the onset of decay.

This study aims at quantifying the impact of material, exposure, and design detailing on the expected service life of wooden components. Therefore various timber structures and commodities were monitored highly frequently in terms of wood moisture content and wood temperature over a period of 3 years. The data sets will be applied to a logistic dose–response performance model, which is based on dose functions considering wood moisture content and temperature as key factors for fungal decay. The response in terms of certain decay levels will be used to characterize different limit states and thus the estimated service lives (ESL).

2 Materials and methods

2.1 Moisture and temperature recording

Wood moisture content and wood temperature were measured continuously and recorded daily on a variety of different timber structures and commodities. Therefore, conductively glued stainless steel electrodes were used for electrical resistance measurements. The measurement system using mini data loggers (Type Materialfox mini, Scanntronik GmbH) has been described in detail by Brischke et al. (2008a). Wood temperature measurements and recordings were made in parallel using mini data logger (Type Thermofox mini, Scanntronik GmbH). Temperature data obtained were used to characterize the climatic load and for temperature compensation of the electrical resistance measurements. Wood species-specific resistance characteristics were used for calculating the wood moisture content after Brischke et al. (2008a).

2.2 Test objects

2.2.1 Object 1: cladding in Tåstrup, Denmark

The objective of this study was to examine the influence of a roof overhang on the moisture conditions within a cladding (Brischke et al. 2008b). Therefore, moisture measurements were conducted on a cladding (15 m long, 2.5 m high) with three different roof overhangs (12, 62, 112 cm) on the test site of the Danish Technological Institute (DTI) in Tåstrup, Denmark (Fig. 1). The data loggers were

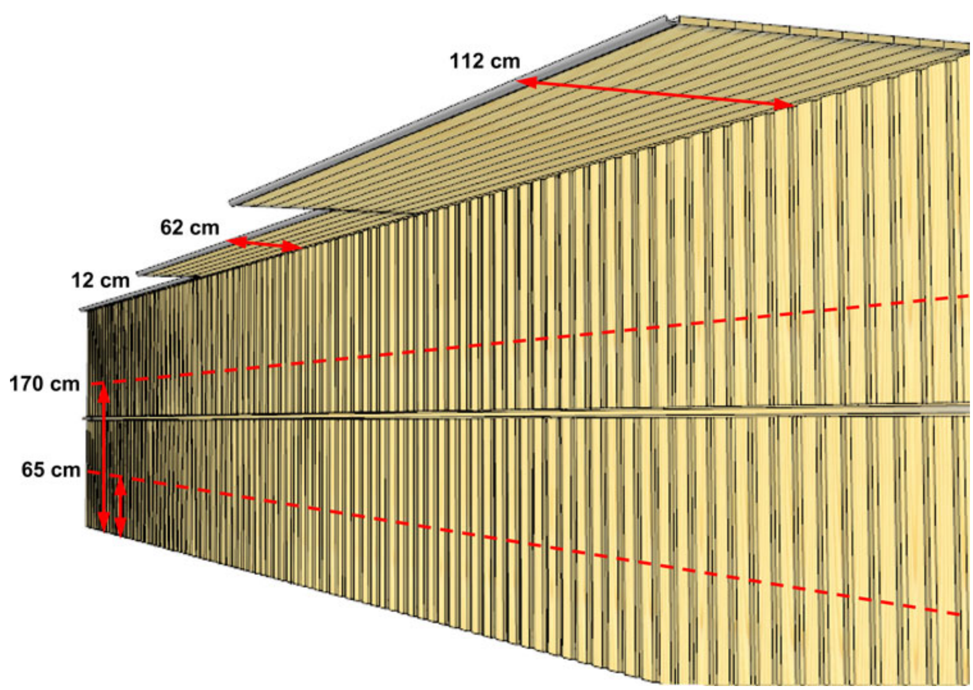

Fig. 1 Board-on-board cladding with different roof overhangs in Tåstrup, Denmark. *Dashed lines* mark the heights of measurement points on the upper and bottom parts of the façade

Abb. 1 Boden-Deckel-Schalung an einer Fassade mit unterschiedlich großen Dachüberständen in Tåstrup, Dänemark. Gestrichelte Linien: Höhe der Messpunkte an der oberen und unteren Fassade

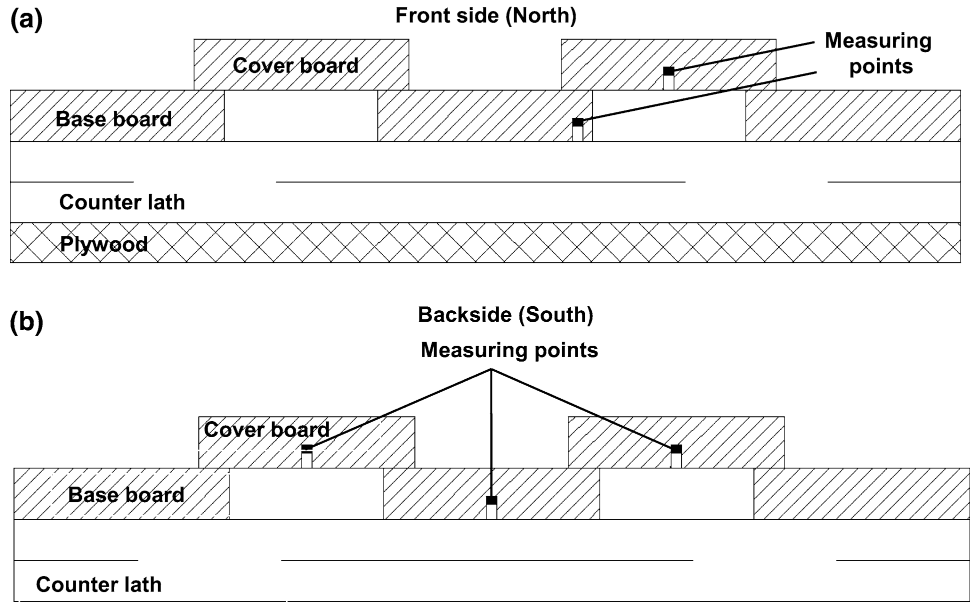

Fig. 2 Cross cut through examined cladding and schematic arrangement of the measurement points. **a** Test assembly in Tåstrup; **b** Test house in Hannover
Abb. 2 Querschnitt durch Boden-Deckel-Schalung an den untersuchten Fassaden. **a** Versuchswand in Tåstrup, **b** Versuchshaus in Hannover

installed in December 2001 and measurements conducted for a period of 3 years between 2002 and 2004. The cladding was made from fine sawn Norway spruce (*Picea abies* Karst.) boards of 1170 × 105 × 25 mm^3, faced to the North, and carried out as a vertical, rear ventilated board-on-board cladding (Fig. 2a). The cladding was split into an upper and a bottom part, each with a height of 117 cm, separated from each other by a horizontal board, acting as a small roof overhang of 4.5 cm width. The distance between the boards of the bottom cladding and the ground was 15 cm. Electrodes for moisture content measurements were glued in from the back of the cladding at two different heights, 65 cm and 170 cm from the ground. In total 18 pairs of electrodes were installed, three for each roof overhang/height combination (Fig. 2a).

2.2.2 Object 2: test house in Hannover, Germany

The impact of wall orientation and the distance to the ground on the moisture induced decay risk was studied on the claddings of a test house, which was built in Hannover–Herrenhausen in December 2008. Moisture content and temperature measurements were conducted for a period of 3 years between 2008 and 2011. The house had a quadratic floor plan of 3 × 3 m^2 and a total height of 3.18 m. The four façades were exactly aligned to the cardinal points of the compass. The stud frame, which was made from Norway spruce, carried a board-on board cladding and a pyramidal broach roof. The roof overhang was minimized to a width of 7.5 cm including the gutter. Five planed test boards of Norway spruce, Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir (*Pseudotsuga menziesii* Franco) were mounted on each side of the building. The spaces in between were filled with so-called blind boards made from Norway spruce. Since the distance between concrete ground and end-grain of the cladding boards was 5 cm, the whole façade was fully rear ventilated.

For measuring the wood MC electrodes were installed at seven different heights: 5, 10, 20, 40, 80, 160, and 240 cm from the bottom end of the boards. Three measurement points per wood species, height and wall orientation were set, which means in total 252 pairs of electrodes. The electrodes were glued in from the back side of the cladding, two pairs in the central cover boards, and one pair in the central base board (Fig. 2b). In addition 84 temperature sensors were installed, one for each parameter combination. Temperature and wood moisture content were recorded every 2 h during the first year and henceforward once a day.

2.2.3 Object 3: fence and terrace decking elements in Hannover, Germany

Continuous moisture and temperature recordings were furthermore carried out on fence posts, pickets and terrace decking between August 2008 and August 2011. Three replicate assemblies were made from planed Scots pine sapwood, Norway spruce, and Douglas fir, afterwards instrumented and exposed on the IBW test site in Hannover–Herrenhausen (Figs. 3, 4). The fence posts were buried directly in the ground; the decking elements were placed on pavers. The whole test field was covered with a water-permeable horticultural foil to protect the test devices from growth of grass and other plants.

Measurement points were set at a depth of 15 mm on differently severe exposed positions on the assemblies: On the fence posts close to the ground, close to the picket, and above the picket; on the pickets close to the post and centrally between two posts; on the decking boards close to

Fig. 3 Decking element; measuring points are marked with *dots*
Abb. 3 Terrassendeck-Element; Messpunkte mit Punkten markiert

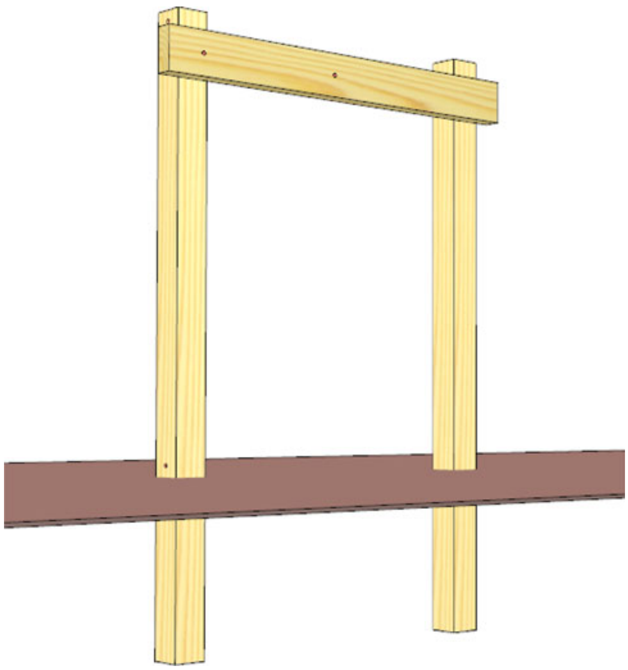

Fig. 4 Fence element; measuring points are marked with *dots* (a fifth non-visible measuring point is located in the post behind the picket)
Abb. 4 Zaun-Element; Messpunkte mit Punkten markiert (ein fünfter nicht sichtbarer Messpunkt befindet sich im Pfahl hinter der Zaunlatte)

the support and centred between two supports; and on the decking supports. For each parameter combination n = 3 moisture electrode pairs and an additional temperature sensor were installed.

2.3 Logistic dose–response performance model (LDR)

Three-year data sets were applied to a performance model describing the relationship between the material climate in terms of wood moisture content and temperature and the corresponding fungal decay. The experimental base for the model have been field test results from double layer above ground trials performed at 28 different test sites in Europe as described by Brischke (2007).

The impact of a general time variation of moisture content u and temperature T on the potential for decay can be described by a dose–response function (e.g. Brischke and Rapp 2010). The total daily dose D is a function of one component D_u dependent on daily average of moisture content u and one component D_T dependent on daily average temperature T.

$$D = f(D_T(T), D_u(u)) \tag{1}$$

For n days of exposure the total dose is given by

$$D(n) = \sum_{1}^{n} D_i = \sum_{1}^{n} \left(f(D_T(T_i), D_u(u_i))\right) \tag{2}$$

where T_i is the average temperature and u_i is the average moisture content for day i. Decay is initiated when the accumulated dose reaches a critical dose.

As described in detail by Brischke (2007) the cardinal points of the parameters wood temperature and moisture content for fungal growth and decay activity were sought and used to set up polynomial base functions for both dose components (Eqs. 3, 4). The total dose D is then calculated as a function of D_u and D_T according to Eq. (5), where D_T was weighted by a factor a.

$$D_u(u) = \begin{cases} 0 & \text{if} \quad u < 25\,\% \\ e \cdot u^5 - f \cdot u^4 + g \cdot u^3 - h \cdot u^2 + i \cdot u - j & \text{if} \quad u \geq 25\,\% \end{cases} \tag{3}$$

$$D_T(T) = \begin{cases} 0 & \text{if } T_{min} < 0\,^{\circ}\mathrm{C} \text{ or if } T_{max} > 40\,^{\circ}\mathrm{C} \\ k \cdot T^4 + l \cdot T^3 - m \cdot T^2 + n \cdot T & \text{if } T_{min} \geq 0\,^{\circ}\mathrm{C} \text{ or if } T_{max} < 40\,^{\circ}\mathrm{C} \end{cases} \tag{4}$$

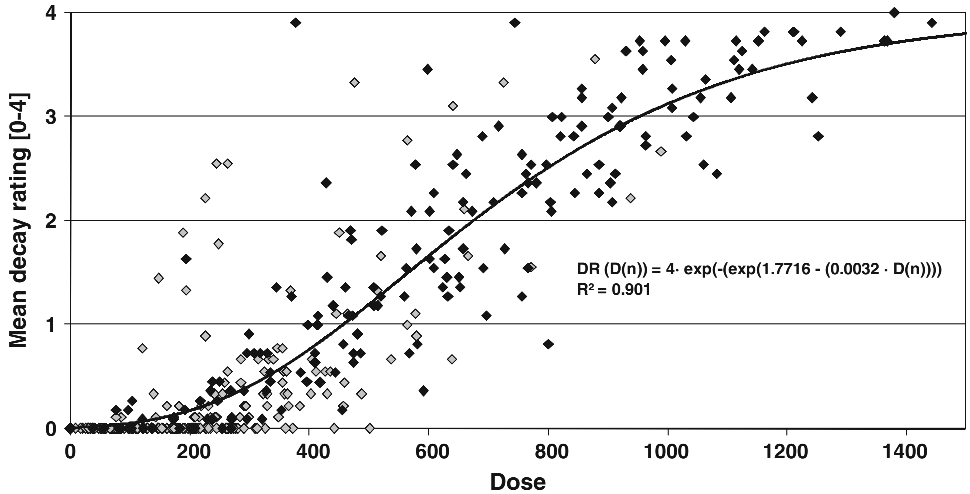

Fig. 5 Relationship between dose and mean decay rating according to EN 252 (1990) of Scots pine sapwood (*black*) and Douglas fir heartwood (*grey*) exposed at 28 different field test sites using a logistic dose–response model (each *dot* represents the mean decay rating at one exposure site at a certain time of exposure; *black line* Gompertz smoothing function) (modified after Brischke and Rapp 2010)

Abb. 5 Zusammenhang zwischen Dosis und mittlerer Abbaubewertung nach EN 252 (1990) von Kiefernsplint (schwarze Punkte) und Douglasienkernholz (graue Punkte) exponiert an 28 Standorten basierend auf einem logistischen Dosis-Wirkungs-Modell (jeder Punkt repräsentiert die mittlere Abbaubewertung an einem Standort zu einem Bewertungszeitpunkt; schwarze Linie: Gompertz-Ausgleichsfunktion (modifiziert nach Brischke und Rapp 2010)

$$D = (a \cdot D_T[T] + D_u[u]) \cdot (a+1)^{-1} \quad \text{if } D_u > 0 \text{ and } D_T > 0 \tag{5}$$

where D = dose [d], D_T = temperature induced dose component [−], D_u = moisture induced dose component [d], u = daily average moisture content [%], T = daily average wood temperature [°C], T_{min} = minimum wood temperature for the day considered [°C], T_{max} = maximum wood temperature for the day considered [°C], a = temperature weighting factor, $e, f, g, h, i, j, k, l, m, n$ = variables.

The best fit for this model against the available data (Brischke and Rapp 2010) was obtained with the following parameters and the final logistic model function according to Eq. (6).

$a = 3.2$
$j = 4.98$
$e = 6.75 \times 10^{-10}$
$k = 1.8 \times 10^{-6}$
$f = 3.50 \times 10^{-7}$
$l = 9.57 \times 10^{-5}$
$g = 7.18 \times 10^{-5}$
$m = 1.55 \times 10^{-3}$
$h = 7.22 \times 10^{-3}$
$n = 4.17$
$i = 0.34$

The total dose over a certain time period is given by Eq. (2) and the decay rating is given by the dose–response function:

$$DR(D(n)) = 4 \cdot \exp(-\exp(1.7716 - (0.0032 \cdot D(n)))) \tag{6}$$

where DR = Decay rating according to EN 252 (1990), $D(n)$=total dose for n days of exposure.

The effect of temperature is dominating on the total dose. The reason for this is that the empirical data from double layer tests used to fit the model is dominated by observations with continuously high moisture content for pine sapwood. The best fit against these data will therefore primarily reflect the effect of temperature on decay rating.

The good fit of the dose response function—as indicated through a degree of determination $R^2 = 0.901$—is illustrated for Scots pine sapwood and Douglas fir heartwood in Fig. 5. However, there were different outliers, where decay developed faster than predicted by the accumulated dose. This happened in particular at the South-Eastern sites Ljubljana and Zagreb, where several specimens had been attacked by brown rot, whereas white and soft rot were dominating at most other sites (Brischke and Rapp 2010).

To prognosticate the service lives of the various timber components examined within this study using Eq. (6), the critical dose D_{crit} was considered according to Fig. 5. The following limit states were defined:

- Mean decay rating 1 (‘slight attack’) acc. to EN 252 (1990)–$D_{crit} = 455$
- Mean decay rating 2 (‘moderate attack’) acc. to EN 252 (1990)–$D_{crit} = 670$
- Mean decay rating 3 (‘severe attack’) acc. to EN 252 (1990)–$D_{crit} = 955$

3 Results and discussion

3.1 Service life prognosis

3.1.1 Roof overhangs

Differently wide roof overhangs influenced the moisture load of the board-on-board cladding of the façade in Tåstrup, Denmark, significantly. Table 1 shows the estimated service life of the cladding for three different limit states referring to decay rating 1 (slight decay), 2 (moderate decay), and 3 (severe decay). The service life to be expected was significantly prolonged through the increasing roof overhang. As expected the biggest differences were observed for the upper part of the façade, where the roof overhang was most effective. The estimated service

Table 1 Mean annual dose according to the LDR model and estimated service lives (SL) for a Norway spruce cladding with different roof overhangs and heights above ground

Tab. 1 Mittlere Jahresdosis basierend auf dem logistischen Dosis-Wirkungs-Modell und vorhergesagte Gebrauchsdauern für eine Fichtenfassade mit unterschiedlich großen Dachüberständen und Abständen zum Boden

Roof overhang	Façade	Board type	Mean decay rating acc. to EN 252 (1990) D_{crit} acc. to Fig. 5 Mean annual dose 2002–2004	Estimated SL [a] 3 955	 2 670	 1 455
112 cm	Upper	Cover	1.09	880	569	386
		Base	1.35	708	497	337
	Bottom	Cover	6.78	141	99	67
		Base	6.46	148	104	70
62 cm	Upper	Cover	5.04	189	133	90
		Base	4.54	210	148	100
	Bottom	Cover	7.86	122	85	58
		Base	6.69	143	100	68
12 cm	Upper	Cover	8.44	113	79	54
		Base	7.51	127	89	61
	Bottom	Cover	8.88	107	75	51
		Base	6.54	146	102	70

Table 2 Mean annual dose according to the LDR model and estimated service lives (SL) of board-on-board cladding at a height of 10 cm above ground for different compass directions and wood species

Tab. 2 Mittlere Jahresdosis basierend auf dem logistischen Dosis-Wirkungs-Modell und vorhergesagte Gebrauchsdauern für Boden-Deckel-Schalungen in einer Höhe von 10 cm zum Boden, unterschiedliche Ausrichtungen und Holzarten

Wood species	Orientation	Mean decay rating acc. to EN 252 (1990) D_{crit} acc. to Fig. 5 Mean annual dose 08/08–08/11	Estimated SL [a] 3 955	 2 670	 1 455
Douglas fir	East	0.00	∞	∞	∞
	South	2.43	393	276	187
	West	3.48	274	193	131
	North	0.00	∞	∞	∞
Scots pine sap	East	0.31	3,081	2,161	1,468
	South	0.00	∞	∞	∞
	West	6.95	137	96	66
	North	1.50	637	447	303
Norway spruce	East	1.86	513	360	245
	South	1.51	633	444	301
	West	5.09	188	132	89
	North	0.96	995	698	474

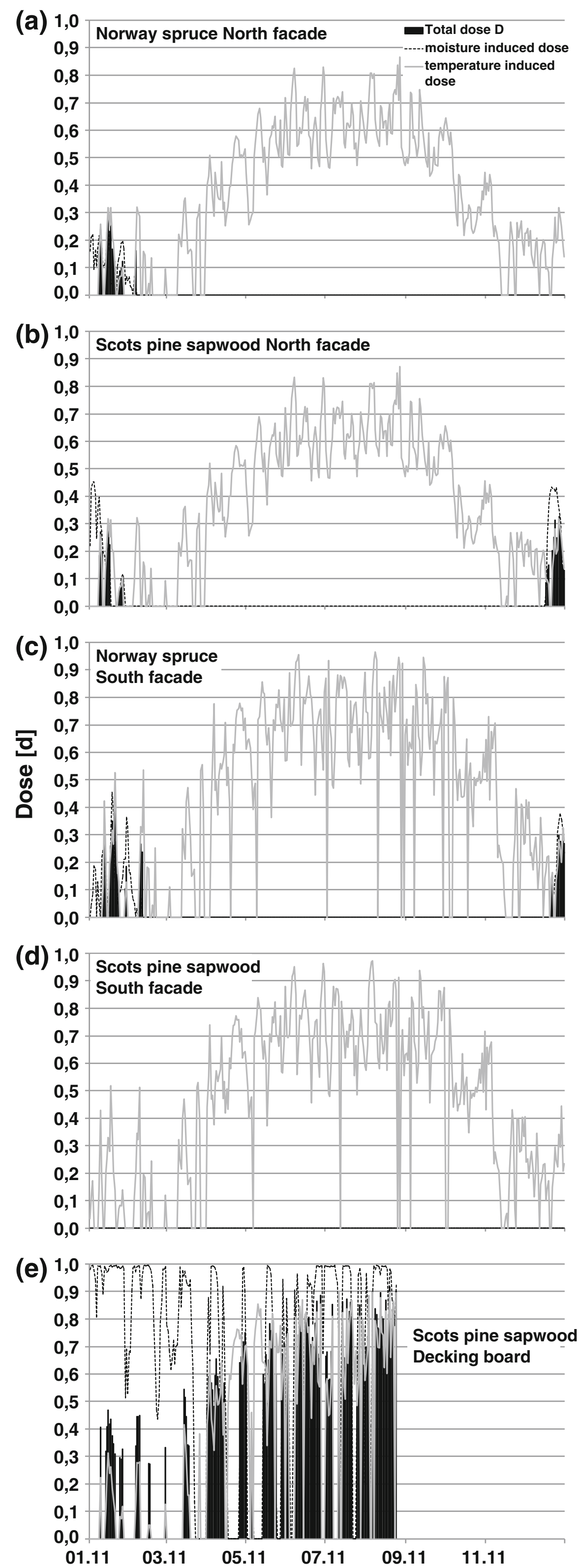

Fig. 6 Development of total dose D and dose moisture and temperature induced dose components D_u and D_T over time during 2011. **a** Norway spruce façade north oriented (5 cm). **b** Scots pine sapwood north oriented (5 cm). **c** Norway spruce south oriented (5 cm). **d** Scots pine sapwood south oriented (5 cm). **e** Scots pine sapwood decking board (measurements of decking boards ended in August 2011)

Abb. 6 Zeitliche Entwicklung der Gesamtdosis und der Feuchte- und Temperatur-induzierten Dosiskomponenten D_u and D_T während des Jahres 2011. **a** Fichtenfassade nach Norden ausgerichtet (5 cm). **b** Kiefernsplintfassade nach Norden ausgerichtet (5 cm). **c** Fichtenfassade nach Süden ausgerichtet (5 cm). **d** Kiefernsplintfassade nach Süden ausgerichtet (5 cm). **e** Kiefernsplint-Terrassendeck (Messung endete hier im August 2011)

lives were up to 8 times higher on the façade with 112 cm overhang compared to that with 12 cm. The maximum estimated service life was 880 years (limit state: rating 3) for the cover boards at the upper façade with 112 cm roof overhang and should be seen as an indication of a non-existing risk of decay rather than a serious estimate. However, the estimates for the bottom part of the façades were more realistic. Considering the onset of decay (limit state: rating 1) the estimates were between 51 and 70 years for the bottom façade and no significant impact of the roof overhang was observed. Only for the upper façade the estimated service life increased with larger overhangs up to 386 years, whereby the sheltering effect of the roof became visible. The moisture loads were furthermore lower for the base compared to the cover boards of the cladding, although the electrodes in the base boards were installed, where they were overlapped by the cover boards and hindered drying could be expected (see measuring points in Fig. 2a).

3.1.2 Wall orientation

In addition to the impact of roof overhang and distance to ground, a third influence factor needs to be considered for service life estimations of wooden façades, which is the orientation of the wall. While in Tåstrup the complete test assembly was faced to the North, the test house in Hannover–Herrenhausen contained of four identically constructed façades exactly oriented to the major compass directions. In Table 2 the estimated service lives are summarized for the four façades at 10 cm above ground, which in general showed the highest moisture induced dose and was therefore the most critical part of the respective cladding.

Compared to the Tåstrup cladding the ESL of the North façade in Hannover were much higher. This is due to several reasons, e.g. different test locations, different test periods, and finally different micro climatic conditions. In contrast to the Danish test site, the Hannover site is protected from wind and thus wind-driven rain from the North through a building and some trees. Such topographical differences can have a significant effect on driving wind loads (Ge and Krpan 2009). In general the wind loads are remarkably lower in Hannover.

However, significant differences between the four different orientations became visible. The highest moisture loads for Norway spruce and Douglas fir occurred on the West façade followed by the South wall leading to minimum ESL of 89 years for spruce (Table 2). Since Southwest is the weather side in Central Europe, the results point to the impact of wind-driven rain and the corresponding moisture loads, which coincides also with findings from Nore et al. (2007), who performed MC measurements on a test house in Trondheim, Norway. In contrast, the Scots pine sapwood also showed highest moisture loads on the West side, but followed by the North façade, which might be explained by hindered re-drying of the very permeable sapwood due to less solar irradiation on the North. The East oriented façade was generally unproblematic, because it is the lee side in Central Europe.

The dose development is illustrated in Fig. 6a–d exemplarily for Norway spruce and Scots pine sapwood on the South and North façade at a height of 5 cm during the year 2011. While the dose of Norway spruce was higher on the South façade (6.49 compared to 2.66 on the North wall in 2011), Scots pine sapwood experienced no moisture induced dose on the South, but a dose of 4.59 on the North wall in the same year. Since the temperature induced dose component D_T was nearly equal for both wood species, but generally higher on the South façade, the decisive influence was the moisture content, which decided between 'dose' and 'no dose'.

Secondly, it became evident that for this particular exposure of a cladding the total dose appears exclusively during the winter. In combination with corresponding low temperatures the total dose is relatively little. For comparison, the total dose D and both dose components D_u and D_T of a Scots pine sapwood decking board are illustrated in Fig. 6e. Here the highest dose values occurred during the summer period with sufficiently high wood moisture content and higher temperatures.

3.1.3 Distance to ground

The second impact factor examined at the test house in Hannover was the distance to ground and thus the influence of splash water on the one hand and differences in re-drying potential due to varying wind speed at different heights on the other hand. In extreme, closeness to ground had an accelerating effect in terms of increasing the moisture loads at the façade.

However, it became not apparent to which extent the higher moisture loads were caused by splash water or by slower re-drying, respectively. Common practice in building guidelines is to avoid timber products up to a height of 30–50 cm above ground, where one should expect significantly higher moisture ingress through splash water (Heikkilä 2005; Gabriel 2009). A general pattern of increased moisture was not detectable for all wood species and wall orientations. However, it became obvious that splash water needs to be considered on walls with high driving rain loads.

In general it became apparent that the exposure conditions of a well-ventilated wooden cladding are comparatively low in terms of moisture, and the resulting estimated service lives are acceptably long in any case, although the studied façades suffered from poor design. These findings coincide with the wide spread use of untreated timber for façades. Even less durable wood species such as Norway spruce are traditionally used for claddings without any preservative treatment in many countries (Davies et al. 2002, 2004; Sellars and Hale 2004). In contrast, higher

Table 3 Mean annual dose according to the LDR model and estimated service lives (SL) for wooden decking made from different wood species
Tab. 3 Mittlere Jahresdosis basierend auf dem logistischen Dosis-Wirkungs-Modell und vorhergesagte Gebrauchsdauern für Terrassendecks aus unterschiedlichen Holzarten

			Estimated SL [a]		
		Mean decay rating acc. to EN 252 (1990)	3	2	1
		D_{crit} acc. to Fig. 5	955	670	455
Wood species	Commodity	Mean annual dose 08/08–08/11			
Douglas fir	Terrace board centre	14.60	65	46	31
	Terrace board at contact face	22.27	43	30	20
	Bearing	32.27	30	21	14
Scots pine sap	Terrace board centre	102.37	9	7	5
	Terrace board at contact face	96.57	10	7	5
	Bearing	66.10	15	10	7
Norway spruce	Terrace board centre	58.93	16	11	8
	Terrace board at contact face	50.83	19	13	9
	Bearing	36.13	26	19	13

Table 4 Mean annual dose according to the LDR model and estimated service lives (SL) for wooden fence elements made from different wood species
Tab. 4 Mittlere Jahresdosis basierend auf dem logistischen Dosis-Wirkungs-Modell und vorhergesagte Gebrauchsdauern für Zaunelemente aus unterschiedlichen Holzarten

			Estimated SL [a]		
		Mean decay rating acc. to EN 252 (1990)	3	2	1
		D_{crit} acc. to Fig. 5	955	670	455
Wood species	Commodity	Mean annual dose 08/08–08/11			
Douglas fir	Picket close to post	1.46	654	459	312
	Picket centred	0.23	4,152	2,913	1,978
	Post above picket	24.41	39	28	19
	Post close to picket	2.60	367	258	175
	Post close to ground	13.16	73	51	35
Scots pine sap	Picket close to post	48.66	20	14	9
	Picket centred	15.75	61	43	29
	Post above picket	46.94	20	14	10
	Post close to picket	20.72	46	32	22
	Post close to ground	76.71	13	9	6
Norway spruce	Picket close to post	13.71	70	49	33
	Picket centred	2.27	421	295	200
	Post above picket	41.28	23	16	11
	Post close to picket	10.48	91	64	43
	Post close to ground	41.06	23	16	11

moisture loads can be expected when wooden components are exposed horizontally and assemblies tend to water trapping.

3.1.4 Terrace and fence

Differently severe exposed details were investigated at typical wooden components. Table 3 shows the ESL for terrace decking made from different wood species, which were between 5 and 31 years to reach limit state ‘rating 1’ (onset of decay). As expected the shortest ESL was obtained for the Scots pine sapwood followed by Norway spruce and Douglas fir. A clear differentiation between the three examined components became not apparent. The bearing revealed the longest ESL for Scots pine sapwood and Norway spruce, but the shortest for Douglas fir. Negative effects of contact faces were not observed, which might be explained by the generally high moisture loads and not very distinct formation of water traps. In contrast, the differences in ESL between fence pickets with and without contact to the fence post were significant for all three wood species (Table 4).

As expected the highest moisture load occurred in the posts close to ground referring to ESLs between 6 years for Scots pine sapwood and 35 years for Douglas fir heartwood. Second severe was the position close to the upper end grain (post above picket) followed by the picket close to the post due to the contact face where drying was hindered. In contrast, the free ventilated picket centre suffered from low moisture loads. In summary, the estimated service lives were found to be plausible, but need to be checked, wherefore decay assessments in all trials will continue.

3.2 Influencing parameters

3.2.1 Impact of test period on service life estimations

One of the major benefits of implementing moisture content measurements into service life prediction models is to save time. To await the onset or progress of decay up to a certain level of wood degradation would require years or even decades, if wood is exposed above ground (Brischke et al. 2012). Continuous wood moisture content and temperature measurements allow estimating the expected service life of timber structures in considerably shorter time, for instance a couple of years. Nevertheless, the annual output of the performance model depends significantly on the climatic conditions of the respective year. As shown in Tables 5 and 6, the ESL of wooden commodities can vary drastically between years; in extreme up to factor 2.6 for cladding with widest roof overhang between 2002 and 2003. The need for extending the measuring periods to a minimum of 3 years to allow the use of an arithmetic mean

Table 5 Estimated service lives ESL (limit state: Rating 2) for a terrace decking made from different wood species, calculated on the base of different years (08/2008–08/2011) according to the LDR model

Tab. 5 Vorhergesagte Gebrauchsdauern (Grenzwert: Abbaubewertung 2) eines Terrassendecks aus unterschiedlichen Holzarten, berechnet auf Basis unterschiedlicher Jahre (08/2008 bis 08/2011) anhand des logistischen Dosis-Wirkungs-Modells

Wood species	Commodity	Year 1 ESL	Year 1 Factor		Year 2 ESL	Year 2 Factor		Year 3 ESL	Year 3 Factor	
Douglas fir	Terrace board centre	51			80			30		
			1.76			**1.82**			**1.25**	
	Terrace board at contact face	29		**1.76**	44		**1.54**	24		**2.73**
			1.00			**0.85**			**2.18**	
	Bearing	29			52			11		
Scots pine sap	Terrace board centre	8			7			5		
			1.1			**0.88**			**0.83**	
	Terrace board at contact face	7		**0.90**	8		**0.58**	6		**0.50**
			0.8			**0.67**			**0.60**	
	Bearing	9			12			10		
Norway spruce	Terrace board centre	16			12			9		
			0.76			**0.92**			**0.90**	
	Terrace board at contact face	21		**1.00**	13		**0.55**	10		**0.47**
			1.31			**0.59**			**0.53**	
	Bearing	16			22			19		

Table 6 Estimated service lives ESL (limit state: Rating 2) for a Norway spruce cladding with different roof overhangs (bottom boards of upper façade), calculated on the base of different years (2002–2004) according to the LDR model

Tab. 6 Vorhergesagte Gebrauchsdauern (Grenzwert: Abbaubewertung 2) einer Fichtenfassade mit unterschiedlichen Dachüberständen (Bodenbretter der oberen Fassade), berechnet auf Basis unterschiedlicher Jahre (2002–2004) anhand des logistischen Dosis-Wirkungs-Modells

Roof overhang (cm)	Year 2002 ESL	Year 2002 Factor		Year 2003 ESL	Year 2003 Factor		Year 2004 ESL	Year 2004 Factor	
112	361			937			453		
		2.84			**6.21**			**2.65**	
62	127		**5.16**	151		**9.37**	171		**4.19**
		1.81			**1.51**			**1.58**	
12	70			100			108		

became obvious. Furthermore, the factors between two different design details or wood species vary from year to year, wherefore also the relative service lives (related to another wooden component) need to be used with care. In principal, the use of a reference component, for instance a horizontal Norway spruce board as suggested by Thelandersson et al. (2011), is a feasible way to become independent from climatic variations between test sites and test years. However, also this relative estimate should be based on a period of at least 3 years to increase reliability. Another option to consider the climatic conditions of the respective test period adequately is to work with reference years (e.g., ISO 15686-1 2011). Therefore a reference year with well defined ‘standard’ conditions is characterized and the test period in question needs to be related to the reference year. This procedure requires however detailed knowledge of the interrelationship between macroclimate, microclimate and the resulting climatic conditions within the material (material climate). First approaches to establish such climate models have been published in recent years (Viitanen et al. 2010, 2011; Brischke et al. 2011; Frühwald Hansson et al. 2012).

3.2.2 Moisture measurements and alternative indicators

The data loggers used in this study were calibrated in a range between 15 and 50 % wood MC and between 4 and 36 °C. Since the electrical resistance of wood depends on numerous factors, e.g., wood species-specific anatomy and chemistry, resistance characteristics were determined for all three wood species examined (Brischke et al. 2008a). With increasing wood moisture content the accuracy of the measurement system decreased but was still indicating a tendency even above fiber saturation. Moisture content below the lower limit of 15 % occurs occasionally on wooden facades and other commodities, but will not be adequately considered by the measurement system applied. However, the relevant moisture range with the fiber saturation point as the lower limit was satisfactorily considered.

Brischke et al. (2012) and Bornemann et al. (2012) reported on different moisture related measures, which may serve as alternative measures of wood durability. Significant differences were found in moisture development over time, time of wetness, and moisture and temperature induced dosage for a variety of native timbers exposed to

different above-ground situations. Nevertheless, a universal 'measure' to compare materials, but also allow for a numeric service life prediction needs to be based on a dose–response performance model (Isaksson et al. 2012). Future studies will also consider the effect of ageing on (a) the electrical conductivity of the material, and (b) the water uptake behavior, which both have most likely a significant effect on service life prognoses (Meyer 2012).

4 Conclusion

Service lives were prognosticated for wooden fence posts, lattices, terrace decking, and façades with different orientation, heights above ground and roof overhangs. Significant differences were found between the various design details and the three investigated wood species. The high frequency monitoring of wood moisture content and temperature turned out to be an efficient and helpful tool. The procedure applied has the potential to save time when testing timber and timber product exposed outdoors—particularly under less severe conditions—because there is no need to await the onset of decay. However, the prediction accuracy strongly depends on the reliability of the performance model in the background. Secondly it became apparent that also for moisture performance based estimates the time, during which the dose is determined needs to be a span of several years to assure adequate consideration of climatic variations between years.

In summary, the use of dose–response performance models can provide service life data to be used for performance based design on the one hand, and opens new alternatives for durability testing of timber and timber products on the other hand. However, for most wood-based materials and potential design solutions moisture performance data are still lacking, wherefore more enhanced studies are needed including the development of reliable models describing the relationship between weather parameters and the material climate.

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